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SUSTAINABLE AND AFFORDABLE RAMMED EARTH HOUSES IN KALGOORLIE, WESTERN AUSTRALIA: DEVELOPMENT OF THERMAL MONITORING TECHNIQUES

Christopher Beckett[1], Daniela Ciancio[2], Christof Huebner[3], Rachel Cardell-Oliver[4]

ABSTRACT: *The cost of construction in remote areas of Australia is extremely high due to the need to transport materials, manpower and equipment over long distances. Due to its use of local materials and labour, rammed earth construction offers a potential solution to this problem. This paper introduces the design, construction and monitoring of two rammed earth houses in Kalgoorlie, WA, being built as part of a project to demonstrate the ability of rammed earth structures to maintain comfortable internal conditions without the need for artificial heating and cooling. The monitoring programme is described and results obtained from a numerical analysis are presented. Results for preliminary testing of in-house developed temperature sensors designed to monitor heat flow through rammed earth walls are also discussed.*

KEYWORDS: Rammed earth, thermal comfort, thermal monitoring, thermal mass, Aboriginal housing

[1] Christopher Beckett, School of Civil, Environmental and Mining Engineering, University of Western Australia. Email: christopher.beckett@uwa.edu.au.

[2] Daniela Ciancio, School of Civil, Environmental and Mining Engineering, University of Western Australia. Email: daniela.ciancio@uwa.edu.au.

[3] Christof Huebner, Institute for Industrial Data Processing and Communication, University of Applied Sciences Mannheim, Mannheim, Germany, c.huebner@hs-mannheim.de

[4] Rachel Cardell-Oliver, School of Computer Science and Software Engineering, University of Western Australia. Email: rachel.cardell-oliver@uwa.edu.au.

1 INTRODUCTION

The cost of construction in remote areas of Australia is extremely high due to the need to transport materials, equipment and manpower over large distances. Many Aboriginal communities are located in these regions. In 2008, the Australian Government committed $5.5bn to the National Partnership Agreement on Remote Indigenous Housing (NPARIH) project to address overcrowding, homelessness, poor housing condition and severe housing shortage in remote Indigenous communities by the end of 2018 through the construction of 4200 new homes and the refurbishment of 4800 existing dwellings [1]. As of the most recent review [1], roughly 1600 new houses have been built and over 5200 refurbished (due in part to incomplete assessments of the conditions of existing stock prior to commencement).

To combat high construction costs, remote area housing generally utilises “transportable” structures, built using prefabricated lightweight, insulated steel frame components. These offer reduced road traffic and construction times as compared to more traditional materials for example fired brick. Despite this saving, the average cost per unit is still high, at around $450,000 (exclusive of infrastructure costs, for example required improvements made to electrical or sewerage services), with these costs expected to rise due to increasing costs of energy [2]. Critically, these costs are also exclusive of maintenance. Given the lightweight nature of these structures and the harsh climates in which they are expected to perform, houses must be provided with Heating, Ventilation and Cooling (HVAC) systems in order to provide comfortable living conditions. The use of such systems is expensive, placing a heavy financial burden on the occupants. Furthermore, the need to build houses quickly has generally led to a poor standard of construction quality, leaving HVAC systems prone to failure, either due to poor installation, overuse or the absence of maintenance, and rendering the houses inhospitable until repairs can be made, if at all possible given their remoteness [3-5]. Such houses are often abandoned, resulting in deterioration and the subsequent need to either be refurbished or demolished if refurbishment costs exceed $200,000. The use of “cheaper” materials for construction is, therefore, self-defeating.

Within the framework of a recently awarded Australian Research Council (ARC) Linkage Grant, the University of Western Australia (UWA) has started a million-dollar project with the Western Australia Department of Housing (DoH) to try to improve the social housing programme in remote Aboriginal communities. The material chosen for this project is rammed earth (RE), identified as a more sustainable, financially efficient and thermally advantageous product as compared to the current transportable construction methods [6]. RE is a construction technique wherein sandy-loam subsoil (United States Department of Agriculture definition) is compacted into formwork in layers to produce a monolithic, free standing structure. In Australia, it is accepted practice to add small quantities (typically 5-10% by dry mass of soil) of stabilising agents (e.g. Portland cement or hydraulic lime) to the raw soil to improve its subsequent strength and durability, as well as to broaden the range of soil types that can be used [7]. As RE largely utilises local materials (i.e. the raw soil) and does not require skilled labour to be transported to site or accommodated, RE houses are more sustainable than the current transportable options. The technique therefore offers a serious economic, environmentally friendly alternative to the use of transportable materials for construction in remote areas.

RE structures generally comprise robust, thick (300mm or larger) external walls which grant them a high “thermal mass”. Thermal mass (sometimes referred to as the “thermal flywheel”) is the product of a material’s density and specific heat capacity and is its ability to absorb and, crucially, store heat. Heat absorption results in lower internal temperatures and provides a heat source at night, resulting in a significant “thermal lag” (i.e. the delay between peak internal and external temperatures), an example of which is shown in Figure 1 [8,9]. The advantages of the use of RE for remote area construction are therefore twofold: on the one hand, construction costs are lower and communities benefit from local employment; on the other, houses are better able to regulate internal temperatures, reducing their energy demand and maintenance costs.

Current regulations for construction in Australia require that all structures obtain a minimum efficiency with regards to their energy performance. The use of highly insulated materials is therefore encouraged in order to reduce the energy loss from the structure to the environment. RE suffers in this regard, as it has very low natural insulative properties (low thermal resistance), and the storative properties of thermal mass are not generally considered in the energy efficiency calculations. Predicted performance of RE structures is therefore significantly poorer than it is likely to be in reality, to the detriment of the RE construction industry. Before RE structures can be considered for remote area construction, therefore, evidence must be provided to demonstrate that predictions made for their thermal performance underestimate the real behaviour of the building. To this end, two RE houses are to be constructed in Kalgoorlie, WA, by the DoH with the aim of providing detailed data regarding the thermal

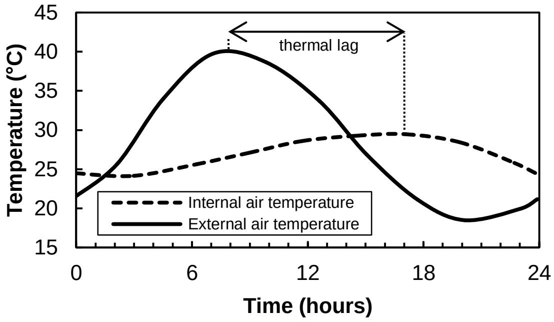

Figure 1: *Internal and external summer air temperatures in a high-thermal mass house in Egypt (reproduced from [8])*

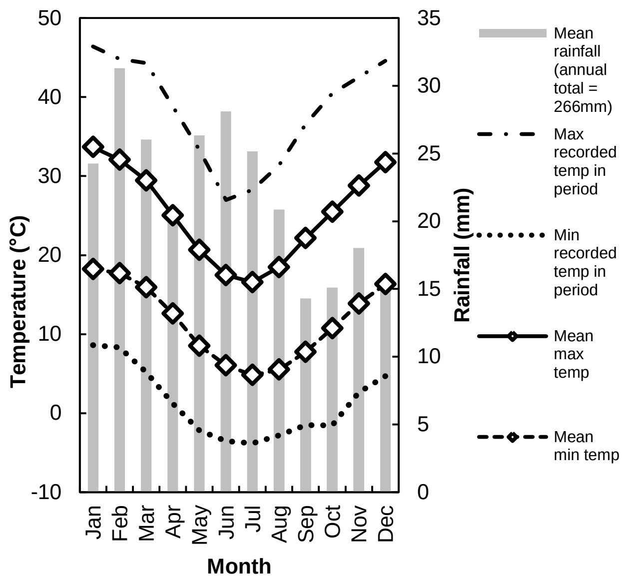

Figure 2: *Climate data for Kalgoorlie (Australian Bureau of Meteorology)*

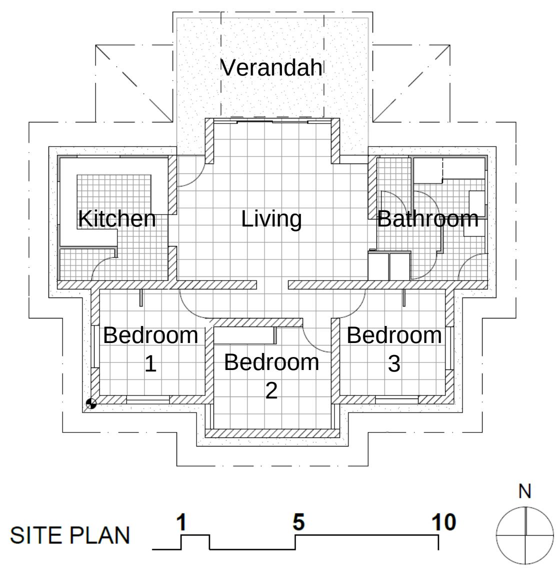

Figure 3: *Design of the insulated and uninsulated RE houses showing principal dimensions. Rammed earth walls are denoted by shading whilst unshaded walls are insulated, lightweight steel frame.*

performance of occupied RE structures, the first such study to be conducted in the world. Kalgoorlie was selected due to its hot, arid climate (Köppen-Geiger Climate Classification [Bwh]), which are conditions necessary to maximise thermal mass thermal regulation properties [10]. Climate data for Kalgoorlie is given in Figure 2. Construction of the houses is also to be monitored in order to determine factors affecting RE quality control.

This paper discusses the development and deployment of the programme for monitoring internal and external conditions in the two RE houses. Preliminary results for the testing of sensors developed in-house are also presented. The design of the two houses and details of the monitoring and laboratory testing programmes are discussed in the following section.

2 MONITORING PROGRAMME

2.1 HOUSE DESIGN

The two houses to be constructed are designed to be identical, save for one comprises uninsulated and the other insulated RE (two RE leaves either side of a central insulating foam panel). The insulated and uninsulated walls are of identical thickness of 300mm. A site plan showing principal dimensions is shown in Figure 3; as both houses are designed to be identical, only one is shown for simplicity. The two houses are positioned close enough to each other to share the same external environmental conditions, whilst being sufficiently separated to not interfere with each other's performance. The houses have primarily been designed to showcase the ability of RE (or indeed all high thermal mass) structures to regulate internal temperatures. The maximum number of RE walls has therefore been included whilst complying with minimum space requirements according to the DoH Public Housing scheme. Shade is provided to all faces of the structure through overhanging eaves and a large verandah has been incorporated on the North wall to provide a shaded outdoor area. A central living area, with the ability to extend it by means of the verandah, is provided to enable large groups to congregate comfortably. Critically, no active heating or cooling systems are present in the houses; ceiling fans and a central flume with attached Venturi fan are included to encourage ventilation but houses otherwise rely on passive heating and cooling.

The two house designs were analysed using Building Code of Australia accredited software (*AccuRate* v2.26) to determine their energy rating and to predict their respective heating and cooling demands. This system awards buildings a "Star Rating" out of 10 where 10 represents structures that do not require heating or cooling to keep habitable areas within a comfortable temperature range and a minimum of 6 is required for construction. *AccuRate* is able to account for the use of different construction materials, location and occupancy variables, for example the opening and closing of doors and windows. A recent study found that *Chenath* engine, used by *AccuRate*, was able to accurately predict the performance of earth-built (high thermal mass, low

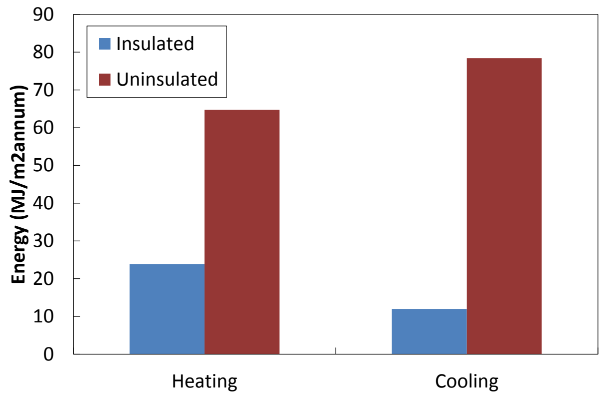

Figure 4: *Predicted heating and cooling loads for the insulated and uninsulated house*

thermal resistance) and brick veneer (lower thermal mass, higher thermal resistance) test houses, suggesting that it is able to account for thermal mass in comfort calculations, at least for those cases [11].
Predicted heating and cooling loads for the insulated and uninsulated RE houses are shown in Figure 4, corresponding to Star Ratings of 8.3 and 6.4 for the insulated and uninsulated houses respectively (analysed in the absence of any active heating or cooling). As expected, heating and cooling demands for the uninsulated house are predicted to be higher than those for the insulated house due to its lower thermal resistance. Interestingly, however, the uninsulated house has a greater cooling demand than heating, whilst the insulated house has a greater heating demand. This could reflect the additional storage capacity of the uninsulated walls, resulting in a greater heat input to the building and so a greater cooling demand.
A shortfall of the *AccuRate* analyses is that thermal comfort levels are not adjusted to account for acclimatization, either through behaviour or upbringing; it is unlikely that Australian and European residents will agree on comfortable temperatures [12]. Furthermore, although results presented in [11] suggest that *AccuRate* is capable of incorporating the beneficial effects of thermal mass into its thermal comfort calculations, it has yet to be demonstrated on the scale of a full-sized, occupied house, for which anecdotal evidence suggests a significantly better performance than that predicted. To investigate this, thermal performance of the two houses will be monitored over the course of twelve months using a series of sensors, with results correlated to occupant's reported comfort levels as assessed by regular surveys, as discussed in the following section.

2.2 THERMAL MONITORING

The proposed layout for monitoring internal conditions during occupancy is shown in Figure 5. Identical layouts will be used per house, however only one house is shown for convenience. Sensors will be installed to monitor *i)* heat flow through the RE walls; *ii)* internal air temperature and humidity in targeted rooms; and *iii)* internal air temperature in remaining rooms.

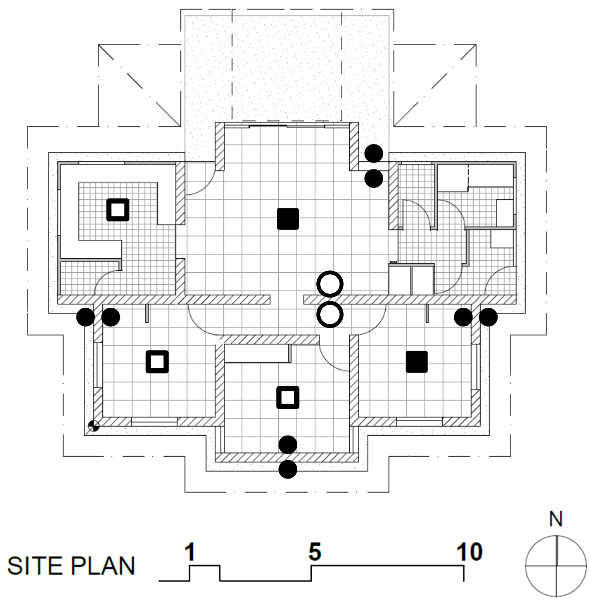

Figure 5: *Locations of heat flow (●,○), air temperature (□) and combined temperature and humidity (■) sensors (dimensions in metres). Shaded walls are rammed earth, unshaded are lightweight insulated steel frame.*

Table 1: *Sensor numbers and locations per house*

Sensor type	Number	Location	Properties
Temperature	12	Embedded	Wall internal temperature
Temperature	12	Surface-mounted	Wall surface temperature
Temperature	3	Ceiling-mounted	Air dry bulb temperature
Temperature and humidity	2	Ceiling-mounted	Air dry bulb temperature and humidity

The total numbers of sensors to be used per house are given in Table 1. These sensors have been selected due to proven reliability and as the authors are already familiar with their use. Due to its remote locations, sensors will be used in conjunction with dedicated data loggers with built-in cellular communication facilities to allow rapid upload to cloud storage without the need for an ethernet connection. Loggers will be housed in the ceiling cavity to avoid damage/tampering. In addition, external conditions (temperature, humidity, rainfall, solar radiation and windspeed/direction) will be monitored via a dedicated weather station (not shown in Figure 5). The weather station also makes use of a cellular data logger to provide easy data access.

2.2.1 Embedded/surface sensors

Heat flow through the RE walls will be monitored by means of sensors embedded in the walls and mounted to the wall surface. A total of 24 sensors will be installed at 5 locations to monitor heat flow, as shown in Figure 5. External wall sensors (symbol ● in Figure 5) will be installed at head height only. Internal wall sensors (symbol ○ in Figure 5) will be installed at both head and knee height, so that the effect of air stratification on heat flow and storage can be investigated. This is of interest as *AccuRate* predictions assume that air is well mixed, which may not be the case in the absence of forced ventilation.
To avoid large amounts of exposed cabling, cables will be routed through the RE walls into the ceiling cavity. To prevent damage, sensors will be housed in protective "trees" during construction, as shown in Figure 6. Trees comprise one vertical (with swept elbow) and one horizontal PVC pipe, terminating in electrical installation boxes. The vertical pipe is of sufficient diameter to house the required number of sensors cables (4 per tree) without snagging, whilst being narrow enough to either fit between the RE leaves for insulated RE or to not interfere with ramming for uninsulated RE. Pipe joints are sealed to prevent water and dust infiltration during ramming. The installation boxes are designed to be large enough to hold sufficient cable to allow sensors to reach their final locations and to sit

flush with the finished wall surface once construction is complete.

Key stages for the installation of sensor trees are shown in Figure 7. The RE wall is rammed up to the desired height and a level surface created, onto which the tree is placed (Figure 7, stage 1). Additional material is then placed on top of the tree and compacted, securing it in place, and wall construction continued up to the desired height (Figure 7, stage 2).

Once construction is complete (but prior to occupancy), installation box covers are removed and the sensor heads exposed. Channels are then drilled into the wall and filled with a sand-cement grout, prior to the insertion of the sensors (Figure 7, stage 3). The use of a grout ensures full thermal contact whilst providing a material with similar thermal properties to that used in the wall, to prevent erroneous results. Surface-mounted sensors will be mounted by means of an insulated plate, to ensure that monitored temperatures are those of the wall surface and not the surrounding air. The advantage of this installation method is that sensors can be extracted and replaced in the event of failure.

As the tree represents a thermal bridge between internal and external surfaces, all sensors will be installed to a minimum of 150mm below the tree invert. Embedded sensors are installed to a depth of 75mm to avoid compromising any insulation. Finally, the installation boxes are filled with foam and covering plates are replaced to prevent heat transfer through the tree branches and through-drafts.

2.2.2 Air temperature and humidity monitoring

Temperature and humidity are two of the key environmental factors governing thermal comfort (another being air movement). Monitoring of these factors will provide quantitative data against which occupant comfort reports can be compared [13].

To reduce data volumes (and interference with the occupants), dry bulb temperature and humidity will be monitored in the living and master bedrooms only. Dry bulb temperature will be monitored in remaining rooms to relate activities in those areas to conditions found in key rooms. Results will then be compared to predictions made by *AccuRate* for each room.

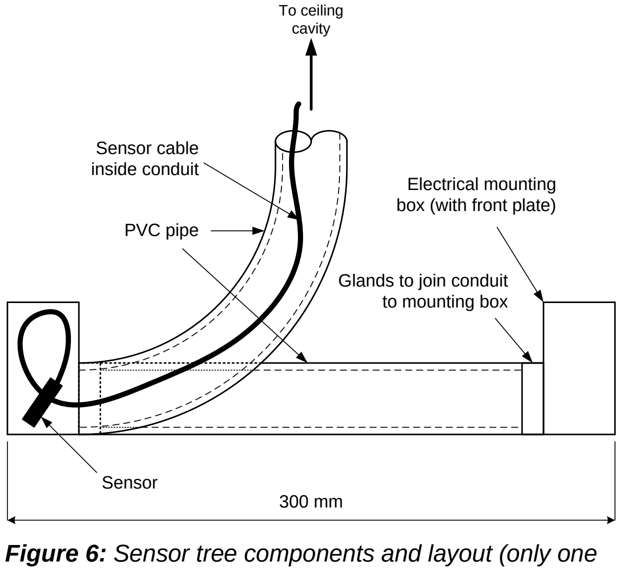

Figure 6: *Sensor tree components and layout (only one cable shown for clarity, not to scale)*

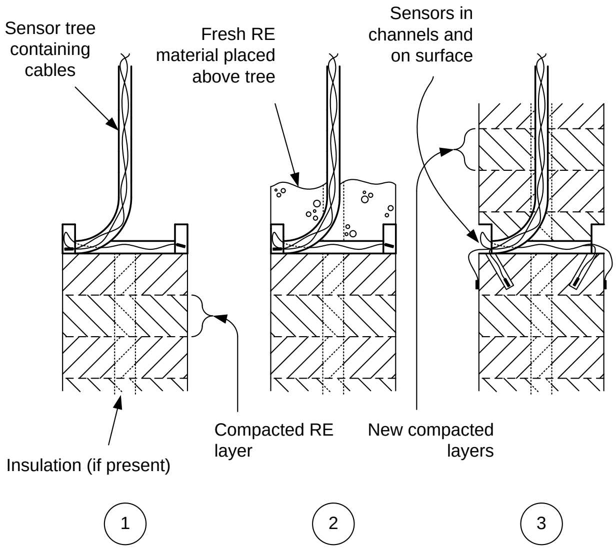

Figure 7: *Installation of sensor trees (surface-mounted sensor cover plates not shown)*

Ideally, internal air properties should be measured at occupant head height away from vertical surfaces. However, such placement would be both inconvenient and invasive, as well as leaving sensors prone to damage. To counter this, a two-month period will be provided prior to occupancy during which embedded sensors can be installed and experiments conducted to relate free air properties (i.e. those away from vertical surfaces) to those measured at ceiling height. This will enable free air properties to be monitored using sensors placed in more secure locations during occupancy and will also allow sensor cables to more easily be routed through the ceiling cavity to the central data logging suite. Additional sensors with built-in logging facilities will also be placed on internal wall surfaces to monitor air temperature at head height, again for correlation with measured free air conditions.

2.2.3 In-house sensors

As discussed above, the commercially-available sensors detailed in Table 1 were selected for use due to a proven capability and user familiarity. However, as a result of their size (a function of their robustness) and required methods of installation, sensors must be placed with a significant gap between them and their neighbours, for example as between embedded and surface heat flow sensors. In-house “strip” sensors were therefore developed in collaboration with researchers at UWA and the University of Applied Sciences, Mannheim, to enable high-resolution temperature monitoring throughout the wall thickness. A sketch of one such strip is shown in Figure 8. Strips comprise several individual temperature sensors with power supplied by a central cable and are designed to be short enough to prevent finished wall surface defects. The number of sensors per strip can be increased or decreased depending on the resolution required: 5 sensors are shown in Figure 8, however it is likely that a higher number will be used. Strips are covered in matte black heat shrinking material

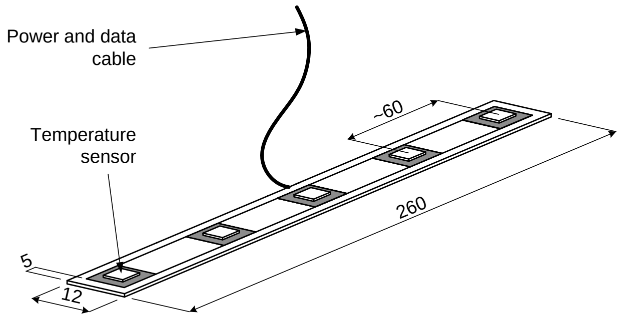

Figure 8: *In-house designed and built temperature sensor (dimensions in mm, not to scale)*

to provide a waterproof coating and to protect against penetration damage which might occur during compaction. The central cable allows cables to be routed via PVC pipes (not shown in Figure 8) via the top of the wall to the ceiling cavity and logging suite, as discussed previously. Strips are to be installed either adjacent or in similar thermal conditions to commercial sensors so that data can be verified.

As strips are embedded, rather than drilled, they offer a method to invisibly monitor heat flow through the material. Unlike the embedded sensors discussed in the previous section, strips do not require the use of a grouting material as full contact with the surrounding material will be achieved following ramming. However, strips, by their nature, are irrecoverable following construction, so that they must be sufficiently robust to survive the ramming process. Test strips were therefore embedded in RE specimens under laboratory conditions in order to test their functionality and survivability. Details and results of this laboratory programme are discussed in the following section.

3 LABORATORY PROGRAMME

3.1 SPECIMEN PREPARATION

RE construction in WA generally utilises crushed limestone, rather than natural soil, due to improved quality control, aesthetic appeal and ready availability. Crushed limestone also has several advantages over natural soil, for example greater consistency in mineralogy and a very low clay content, which endears it to cement stabilisation [14]. Crushed limestone was therefore selected for use in this investigation. Note that the aim of this investigation is not to reproduce site material, but to imitate site conditions to determine

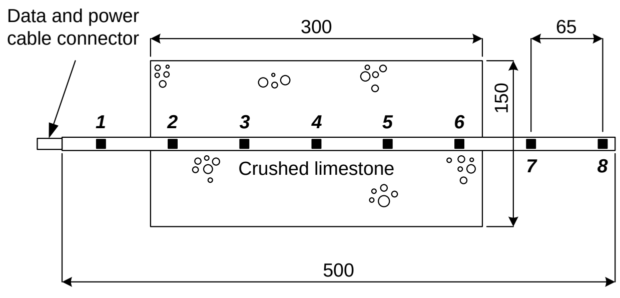

Figure 9: *Placement of temperature strip in test specimen (sensor numbers in italics, dimensions in mm)*

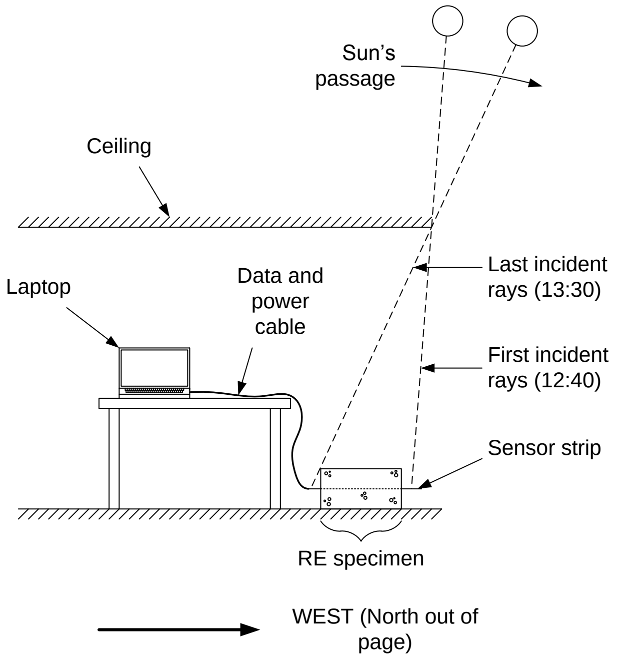

Figure 10: *Experimental setup for test (i)*

sensor survivability, so that the use of a material different to that likely to be used on site is justified.

Crushed limestone was oven-dried for 24 hours at 105°C prior to being sieved to remove particles larger than 10mm. Although particles of up to 20mm might be encountered during construction, the reduced particle size is necessary due to the use of considerably smaller moulds in the laboratory than the formwork used on site. Once sieved, crushed limestone was mixed with 5% Portland cement by dry mass of limestone. This is again typical of RE construction in WA, however higher cement contents are also used.

Wetted material was compacted in even layers into a 300×150×150mm steel mould up to a depth of 75mm. A 500mm sensor strip comprising 8 temperature sensors at 65mm intervals was placed on top of the compacted surface, the ends of which protruded from the mould through slots cut into the sides as shown in Figure 9. Additional material was then rammed on top of the sensor in even layers up to the full mould height of 150mm.

It is usual to remove stabilised RE specimens from their moulds within 24 hours of manufacture and to cure them for an additional 27 days in highly humid conditions prior to testing, in order to ensure complete cement hydration. However, as material strength was not a concern for this investigation, the specimen was left in its mould for the duration of testing.

The specimen was moved to a controlled environment and temperatures allowed to equilibrate to ambient conditions (approximately 20°C) immediately following manufacture. Temperatures were continually monitored during this period to ensure equilibration and sensor functionality. Two tests were then conducted: *i)* rapid exposure to direct sunlight to simulate the behaviour of an external wall under high daily thermal load; and *ii)* long-term monitoring under shaded (i.e. no direct sunlight) conditions to simulate the performance of an internal wall exposed to more gradual changes in internal air temperature. Temperatures were recorded every 10 seconds. This is a much higher sampling rate than will be used in the field, however it was warranted due to the shorter duration of laboratory testing. A sketch of the experimental setup for test *(i)* is shown in Figure 10. For test *(ii)*, the setup was left unchanged however shade was provided to prevent direct sunlight from striking any part of the apparatus. Results of these tests are discussed in the following section.

3.2 RESULTS AND DISCUSSION

3.2.1 Test *i)*: External wall simulation

Results for the exposure of the RE test specimen to gradual direct sunlight are shown in Figure 11. The point at which direct sunlight strikes the sensors is demonstrated by a sudden temperature spike for sensors 7 and 8. A smaller spike is seen for sensor 1 due to the specimen's own shadow reducing the sun's impact (as seen in Figure 10).

As the sensors are provided with a matte black coating, temperatures recorded by sensors exposed to direct sunlight are not representative of air temperature but rather the sensor's own surface temperature. Regardless, a significant lag (roughly 3 hours) is seen in Figure 11 between peak internal and external temperatures, with sensors located nearer the specimen's centre showing greater lags than those towards its edges. Although affected by the presence of the steel mould, these results nonetheless indicate that a significant lag can be achieved even in a small specimen. The difference in peak temperatures is also worth noting, however again this is exaggerated due to the effect of direct sunlight. This test therefore shows that the sensor strips are able to survive the ramming process and are subsequently able to generate detailed data for internal temperature changes and the role of thermal mass.

3.2.2 Test *ii)*: Internal wall simulation

As discussed above, exposure of sensors to direct sunlight results in unrealistic measurements of ambient air temperature. As a result, a second test was set up to monitor temperature changes throughout the specimen due to changes in air temperature only, indicative of performance of an internal wall.

Results for test *(ii)* are shown in Figure 12, with

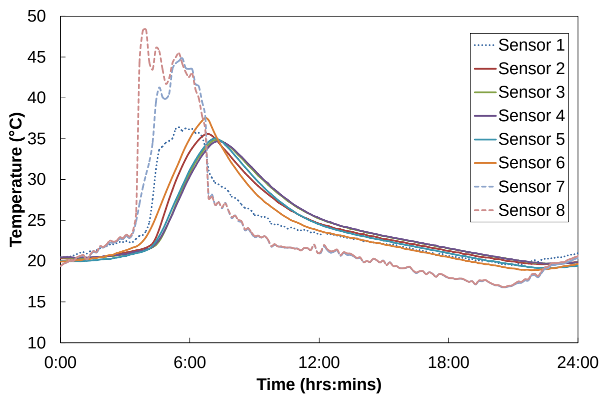

Figure 11: *Exposure of test specimen to incident summer sunlight*

extracted 2 and 3-day periods shown in Figure 13 and Figure 14. Note that a period of 72 hours was used to ensure that the specimen was responding consistently to changes in surrounding air temperature, so that results presented are for after this period. Given the high thermal conductivity of the surrounding steel mould, values of thermal lag are, as opposed to the case for direct sunlight, suggestibly representative of those arising from the RE specimen's thermal mass only.

Unlike those shown in Figure 11, results for test *(ii)* do not show any sudden temperature spikes, indicating that incident sunlight was not present and that shading of the specimen was successful. Figure 12 shows that significantly higher temperatures were found for external air than occurred internally; this is clear to see in Figure 13 and Figure 14, where a difference of 5°C occurred

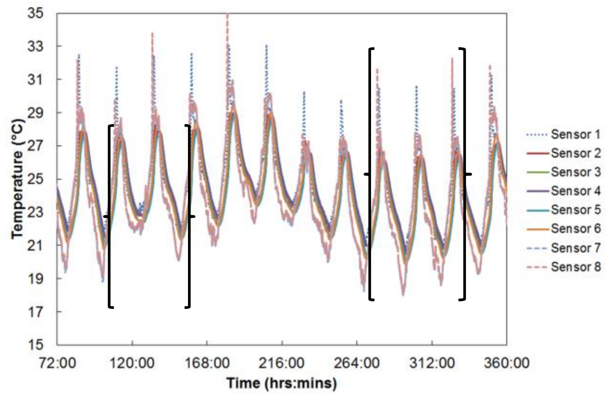

Figure 12: *Results for test (ii) with highlighted 2 (left) and 3 (right) day periods*

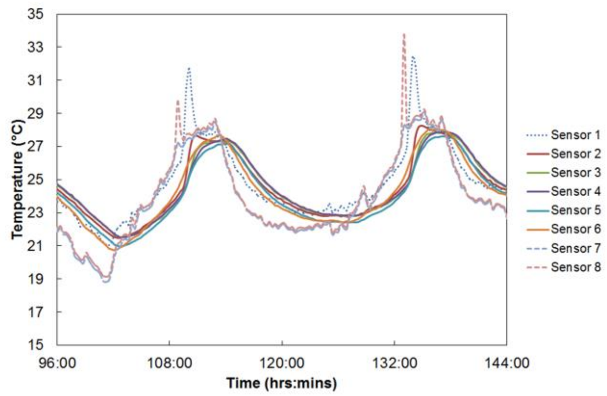

Figure 13: *Extracted 2-day period from test (ii) results*

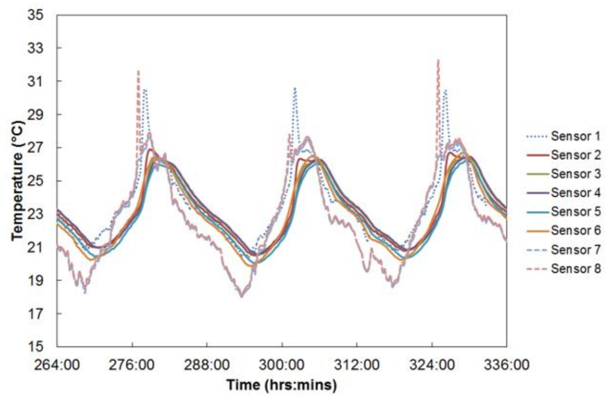

Figure 14: *Extracted 3-day period from test (ii) results*

between peak external and internal temperatures. Figure 13 and Figure 14 also show a considerable lag between these peak temperatures of roughly 2 hours for sensor 2 and up to as much as 5 hours for sensor 4, with similar results evident for other days shown in Figure 12. Lags of between 2 and 3 hours are also seen between the lowest recorded temperatures, with sensors towards the centre of the specimen recording higher temperatures than those towards the extremities, indicating greater heat storage towards the specimen's core.

Results presented in Figure 11 and Figure 12 therefore show that the sensor strips can not only survive installation, but are then able to provide detailed information concerning heat flow through the material under both high and low heat loads over long testing periods. At time of writing, long-term testing under both high and low heat loads is continuing in order to determine sensor longevity, an important consideration as sensors are irrecoverable once installed and must function without fault for the entire 12-month testing period. Should this prove successful, it is anticipated that these sensors will be deployed in a wide range of RE structures to monitor heat flow and to assist in the development of optimal thermal designs for specific regions.

4 CONCLUSIONS

This paper has discussed the issues facing construction in remote areas of Australia and has argued the potential benefits afforded by RE construction. Initial laboratory results for the testing of in-house embedded sensors have also been presented and discussed.

A UWA-DoH joint project aimed at demonstrating the ability of RE structures to comfortably regulate internal temperatures without the need for expensive, energy-intensive air conditioning systems has been introduced. As part of that project, two test houses, one comprising insulated and the other uninsulated RE, will be constructed in Kalgoorlie, an arid region of inland WA, and conditions within them monitored over the course of twelve months' occupancy. Factors considered in the design of each house have been examined and the designs analysed using the *AccuRate* thermal performance software, showing that both houses achieve the minimum required energy efficiency ratings. Shortfalls with the *AccuRate* system have been discussed and it has been argued that performance of the RE houses is likely to be better than that predicted due to the material's high thermal mass and the software's use of inappropriate thermal comfort criteria. The monitoring programme aimed at investigating this observation has been described, including the selection of commercially-available sensors and processes to be used in their placement. The need to develop in-house sensors for detailed monitoring of heat flow through RE walls and elements of their design were also discussed.

A laboratory testing programme was conducted to determine whether in-house developed sensors could survive the compaction process. Results obtained showed that sensors continued to operate following compaction and were able to provide detailed information regarding heat flow into and out of a test specimen under both high and low thermal loads for long testing durations. It is therefore hoped to deploy these sensors in the field, to be used in conjunction with commercially-available sensors, to enable heat flow through internal and external (insulated and uninsulated) RE walls to be examined. This will greatly contribute to the development of optimal thermal designs for RE structures in specific regions.

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